Propagation Delay Prediction of Interplanetary Shocks to Earth's Magnetosphere

An Investigation of Methods

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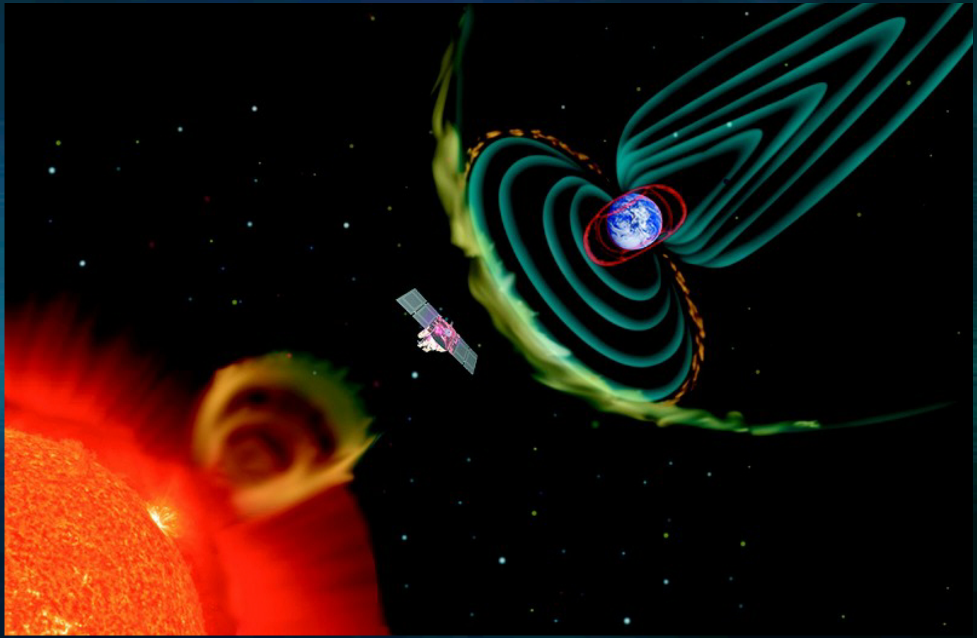
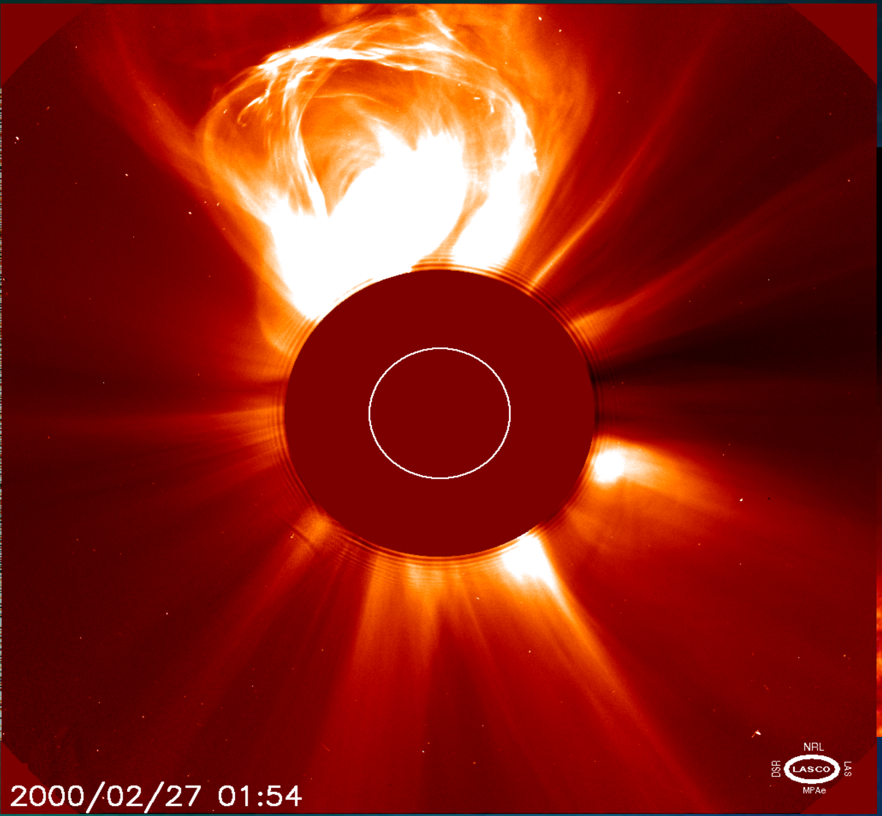
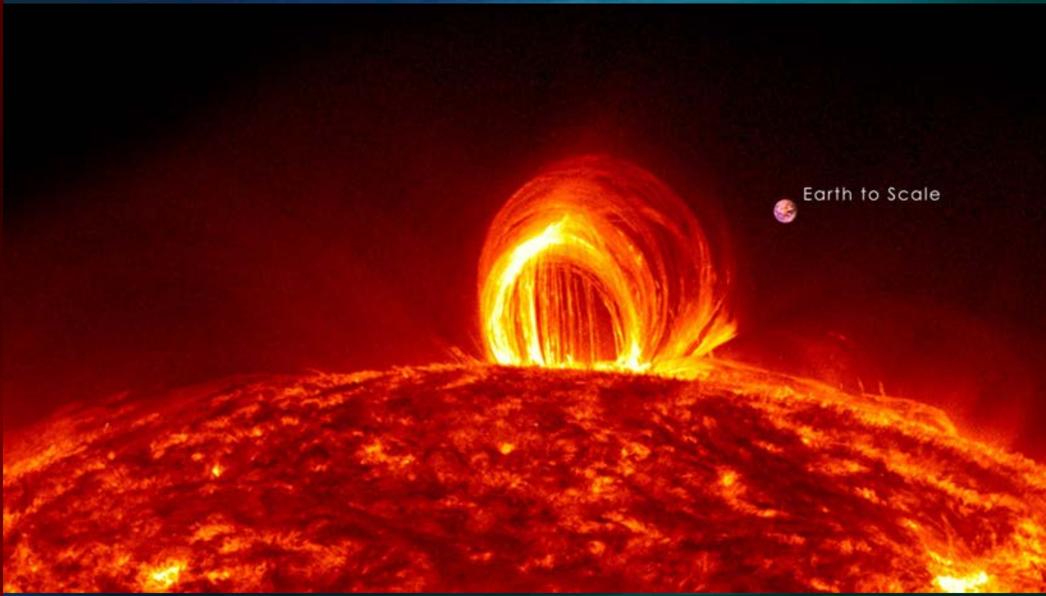


A few solar phenomena

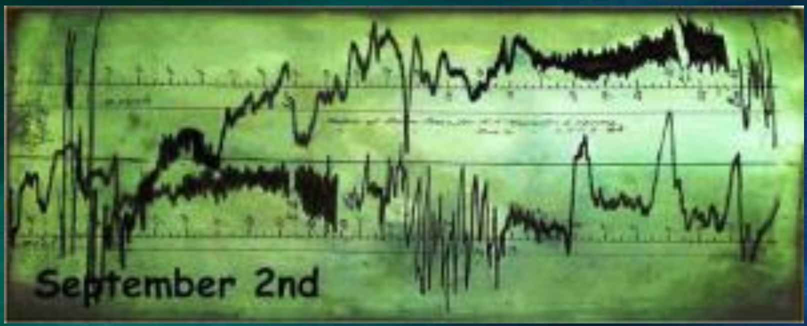


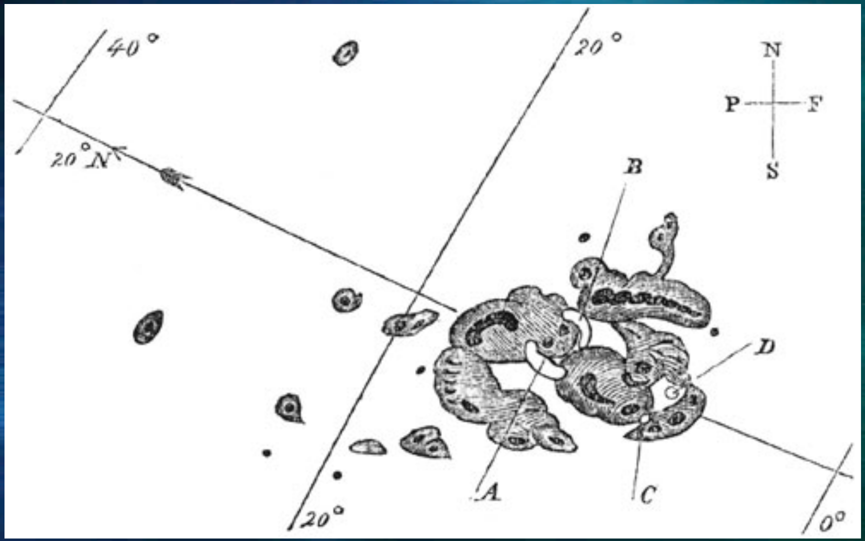


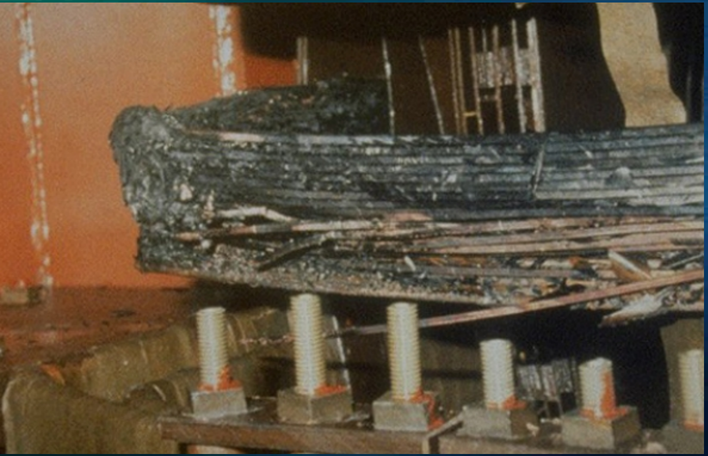
- X-Ray radiation
- Increased proton/electron flux in the solar wind
- Large and fast-moving plasma clouds (CMEs)

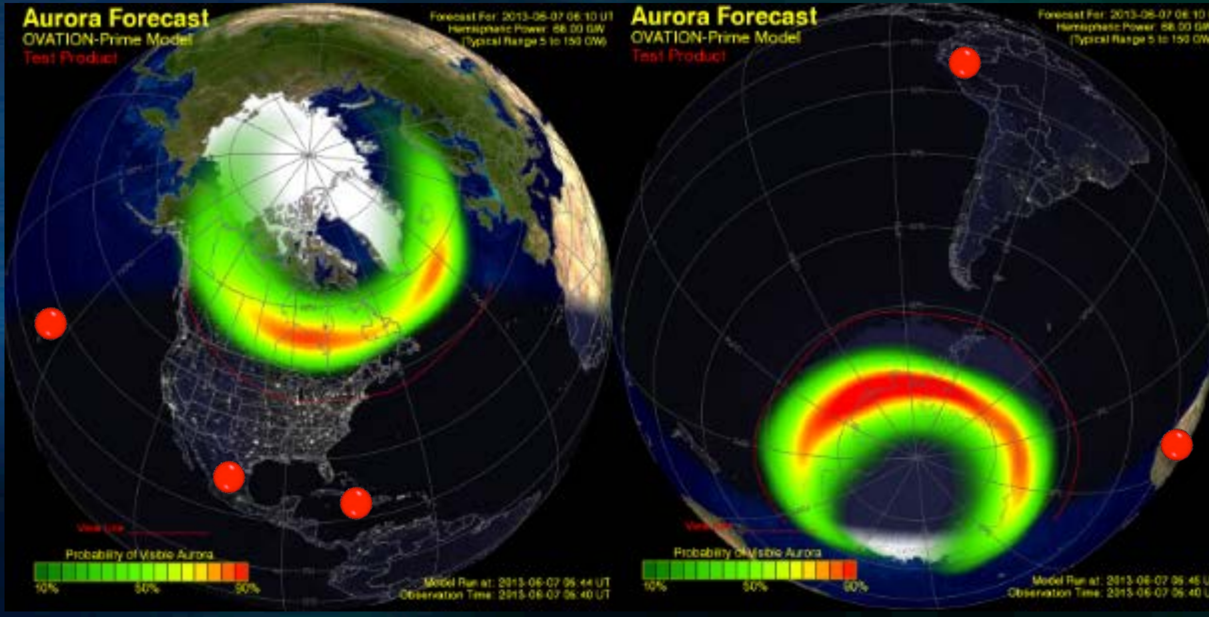
Shock

The Carrington Event

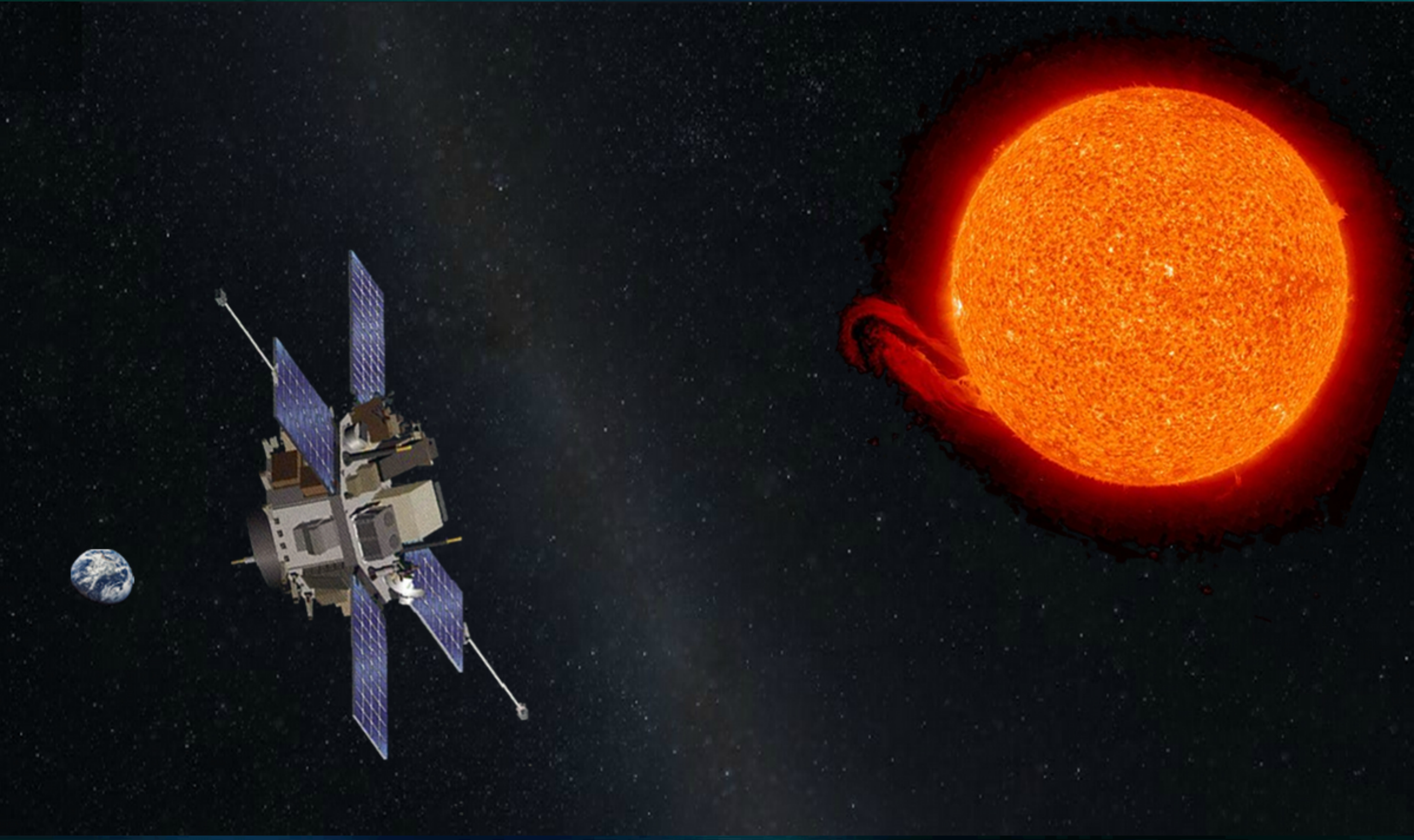








Space Weather Forecasting

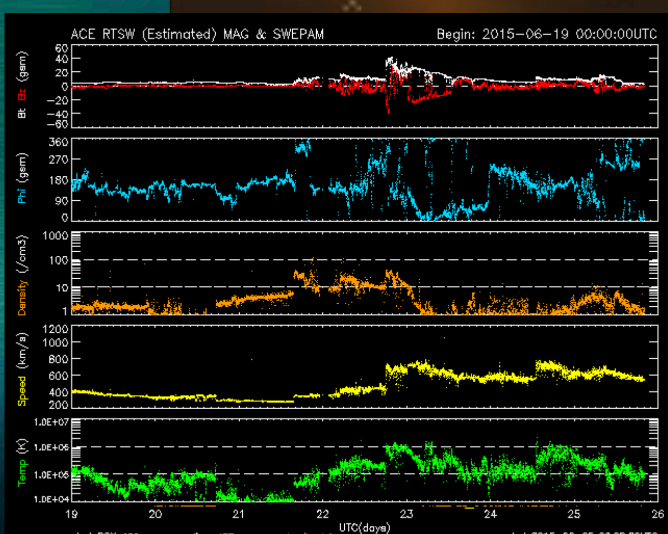


ACE

- Launched Aug 25, 1997

DSCOVR

- Launched Feb 11, 2015
- Reached L1 orbit June 8, 2015



Methods for predicting time delay from L1 to Earth

Convection Delay

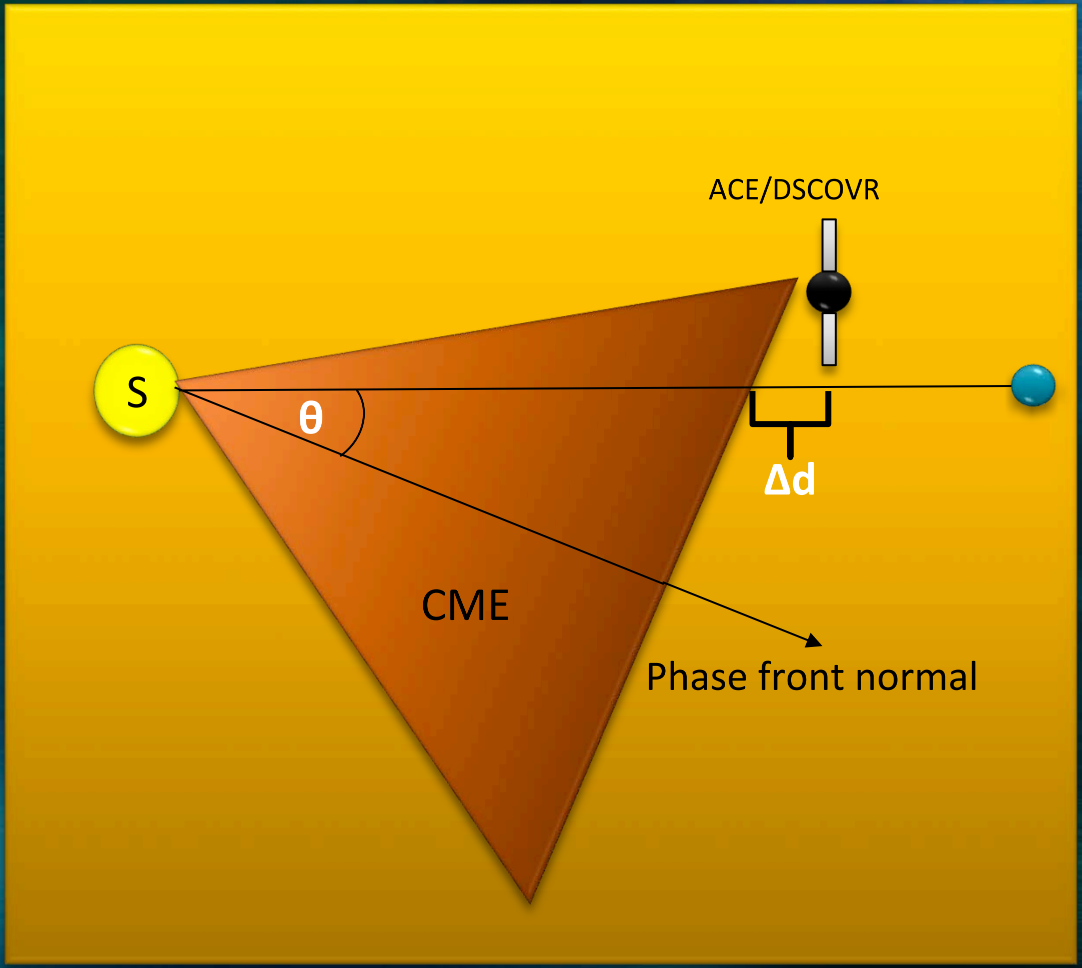
From L1 to Earth

$$t = d / v \qquad (1)$$

Of shock front

Collier et al. [1998] - found results were accurate to within 10% for about two-thirds of all cases

Hypothesized shock geometry



Ridley [2000] conclude that a better method is needed to determine the tilt of solar wind phase Planes, especially during periods of large S-E separation.

Minimum Variance Analysis (MVA)

- *Weimer et al.* [2003] - shows that the MVA "performs reasonably well for predicting the actual time lags".

However…

Weimer et al. [2004] - corrects that MVA worked only due to a "serendipitous program error, which calculated a 'modified variance Matrix'".

Bargatze et al. [2005] - notes that this modified variance matrix produces identical results to the MVAB-0 method.

MVAB-0

MVAB-0 Calculation

$P_{ij} = \delta_{ij} - \hat{e}_i\hat{e}_j$ [projection matrix P] (2)

$\lambda max / \lambda int$ > threshold

$M\downarrow ij = \{B_iB_j\} - \{B_i\}\{B_j\}$ [3x3 variance matrix M] (3)

$Q_{nk} = P_{ni}M_{ij}P_{jk}$ [MVAB-0 matrix Q] (4)

Solve for eigenvectors of Q (i.e. x_1, x_2, x_3) and corresponding eigenvalues (i.e. $\lambda_1, \lambda_2, \lambda_3$)

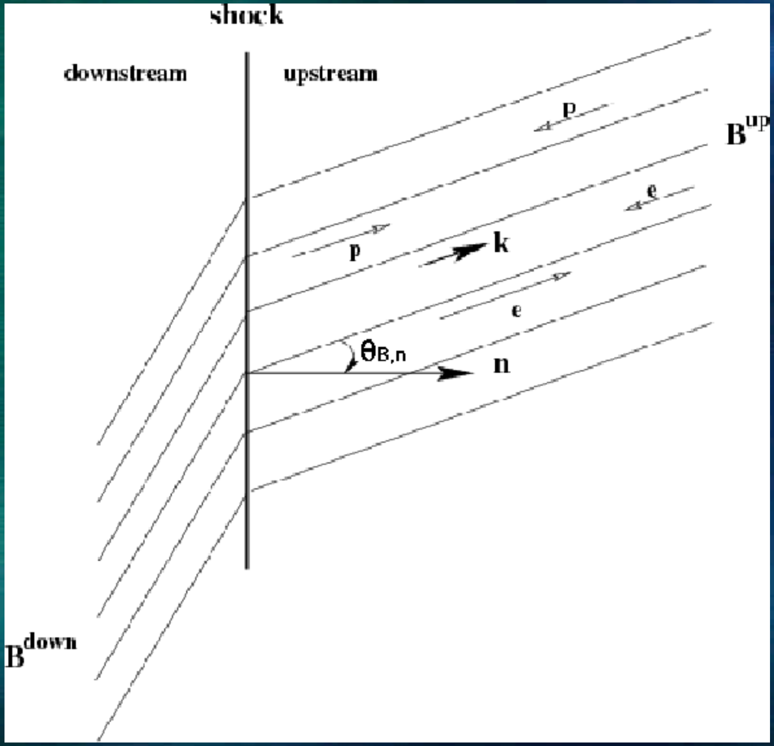
$M\downarrow ij\, x = \lambda x$ *(5)*

The smallest eigenvalue = 0 and the corresponding eigenvector is in the direction of the average magnetic field (i.e. direction of the phase front normal (PFN))

Cross Product method (CP)

$B\downarrow u \quad x\, B\downarrow d$

(6)



Condition:

ω > threshold

The spreading angle between upstream and downstream magnetic fields must be sufficiently large

Tested with shock arrival-time prediction by *Horbury et al.* [2001]

Tested for shocks normal calculation by *Knetter et al.* [2004]

Tested with solar wind by *Weimer and King* [2008]

MVCP
(Minimum Variance + Cross Product)

Criteria for valid tilt

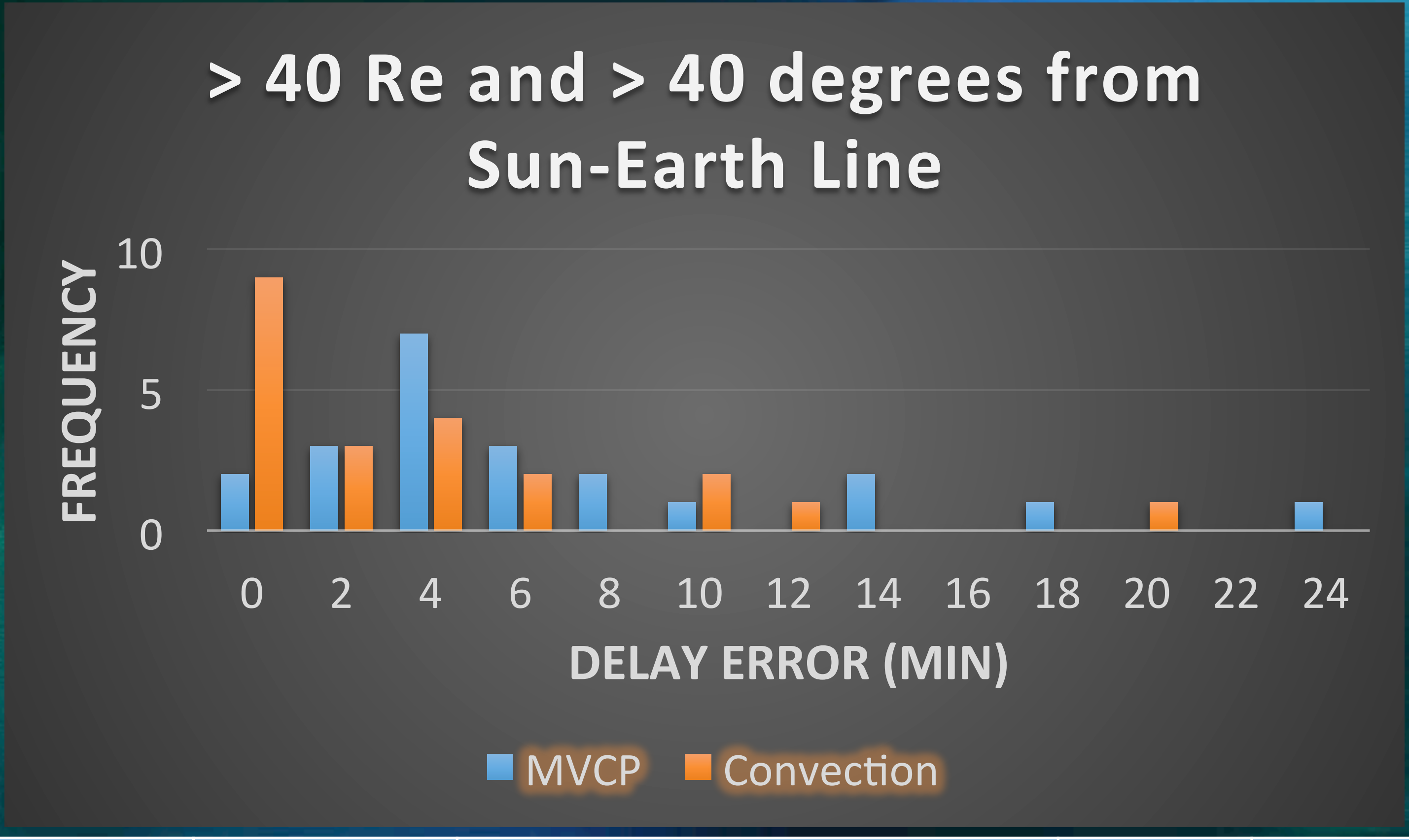
ω > threshold **AND** $\lambda max / \lambda int$ > threshold

Suggested by *Weimer and King* [2008]

Pros/Cons of Each Method

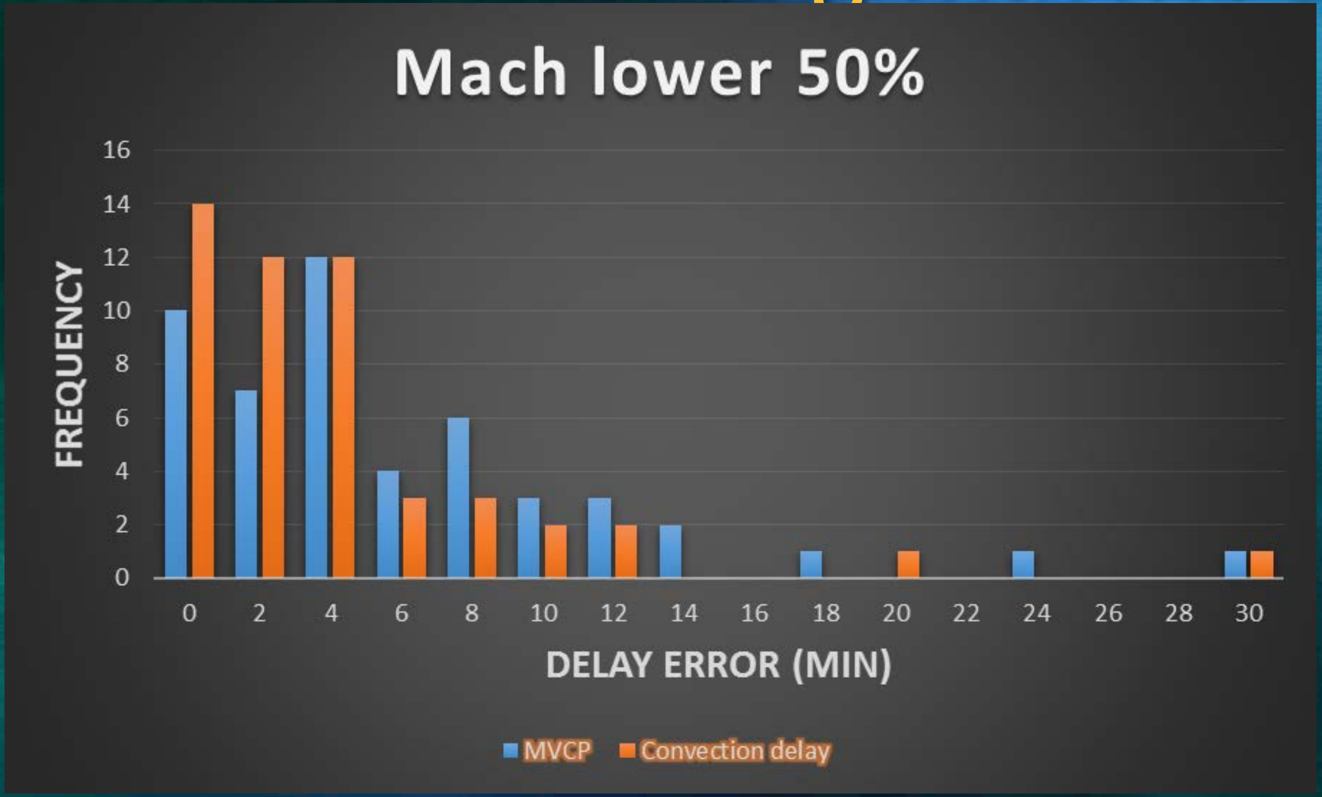
	Convection Delay	MVAB-0	Cross Product	MVCP
Pros	Computationally and conceptually simple	Accounts for shock tilting	Accounts for shock tilting Computationally simple Tested by previous researchers for shock forecasting	Accounts for shock tilting Recommended by *Weimer and King* [2008] for use in solar wind forecasting
Cons	Flat plane “ballistic” propagation (i.e. doesn’t account for shock tilting)	Computationally complex Not tested for use in shock forecasting	I couldn’t think of any when I started; can you?	Most computationally complex (slightly more than MVAB-0)

Correlation Hunting with MVCP



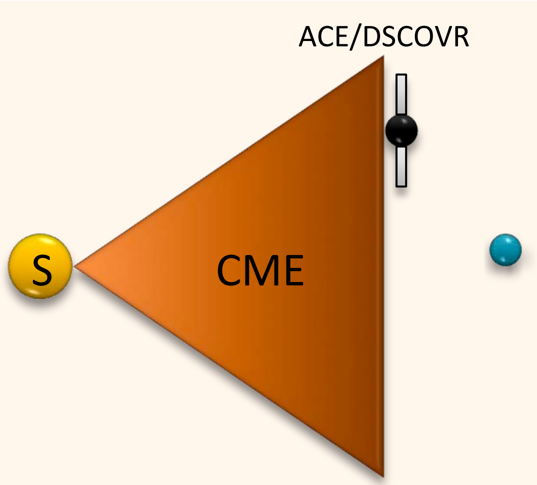
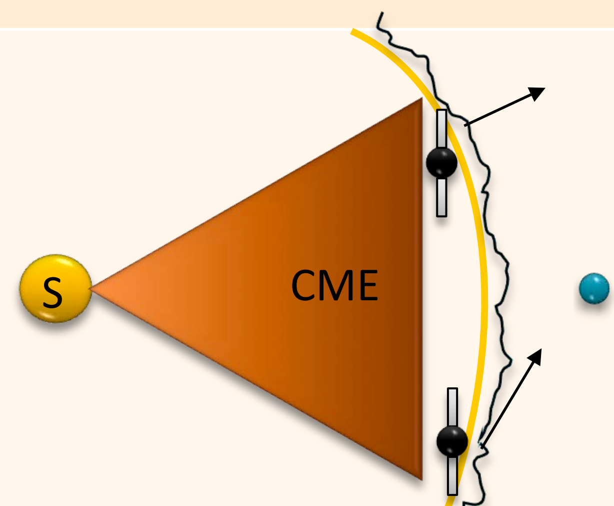
		FREQUENCY OF ERROR IN PREDICTED ARRIVAL TIME (%)				
Hypothesis	SHOCK PARAMETER	0-5 min error	6-11 min error	12-31 min error	Mean error (min)	Data Summary
When ACE is far from the S-E line and observes a shock that is highly tilted away from the S-E line, a tilted-phase-planes method corrects for the error seen in convection delay.	ACE >40 R_E & SHOCK TILT >40^O FROM S-E LINE **CD** **MVCP**	**73** **55**	**18** **27**	**9** **18**	**4** **7**	**Convection delay outperforms MVCP for highly-tilted/far events.**

Correlation Hunting with MVCP



		FREQUENCY OF ERROR IN PREDICTED ARRIVAL TIME (%)				
Hypothesis	SHOCK PARAMETER	0-5 min error	6-11 min error	12-31 min error	Mean error (min)	Data Summary
A strong shock (Mach # used as a measure of strength) will be less susceptible to tilting if it simply blasts through the solar wind, so it will travel with a relatively flat phase front plane. Thus, a tilted-phase-planes method will better predict weaker, more tilted, shocks.	MAGNETOSONIC MACH NUMBER UPPER 50% CD UPPER 50% MVCP LOWER 50% CD LOWER 50% MVCP	76 58 74 58	16 26 17 32	8.0 16 9.4 9.4	4 6 4 5	Convection delay outperforms MVCP for both strong and weak shocks.

What could the results mean?

In general, shocks travel with relatively flat phase front planes	A shock’s structure does not have a uniform tilt that can be predicted with our normal-calculation methods
Not likely – lots of research to back up tilts	The phase-front structure of a shock is more complex than simply flat or simply tilted. A phase-front structure may have multiple, smaller tilts. A tilted-phase-planes method may accurately predict *one* given tilt, though it may not describe a shock’s orientation in general.
 	

Broadening the Search

When a flat-plane propagation method (convection delay) began to look more valid than the MVCP method, we changed the algorithm to calculate MVAB-0 and Cross Product arrival predictions as well.

	FREQUENCY OF ERROR IN PREDICTED ARRIVAL TIME (%)				
PREDICTION METHOD	0-5 min error	6-11 min error	12-31 min error	Mean error (min)	Data Summary
Convection delay	76	17	7.8	4.32	Convection delay outperforms ALL tilted-phase-planes methods, on average
MVAB-0	67	18	15	5.73	
Cross Product	58	26	16	6.23	

Parameter Optimization

Parameter	Optimized Values for this data set
Data Cadence	1 minute
Limiting Angle	60
Number of Points in CP Average	3
Number of Points in MV Calculation	7
Agreement Angle	22
Minimum Eigenvalue Ratio	27
Minimum B Change Angle	1
Step Size	2
Number of Points in Shock Average	1
For Invalid Tilt Angles	Assume flat plane

New SI list		
	Skill Scores comparing methods to convection delay	
Method	**Optimized Parameters**	**Original Parameters**
MVCP	.04 ± .02	-.035 ± .015
MVAB-0	.031 ± .013	-.07 ± .03
CP	-.08 ± .03	-.07 ± .03

Error guidelines set forth by John R. Taylor in *An Introduction to Error Analysis*, 2nd ed.

Using skill scores to determine best method

Blue= overlap (one method does just as well as another within the error bars)

Green= no overlap (one method performs significantly better or worse than the other methods)

New SI list – (subset of ACE Science Center List)		
Percent Improvement on Convection Delay		
Method	**With Parameters Optimized**	**With Original Parameters**
MVCP	4 ± 2	-3.5 ± 1.5
MVAB-0	3.1 ± 1.3	-7 ± 3
CP	-8 ± 3	-7 ± 3

The cross product method does not perform as well as the other two tilted-phase-plane methods within the error bars.

Using skill scores to determine best method

Blue= overlap (one method does just as well as another within the error bars)

Green= no overlap (one method performs significantly better or worse than the other methods)

New SI list – (subset of ACE Science Center List)		
Percent Improvement on Convection Delay		
Method	**With Parameters Optimized**	**With Original Parameters**
MVCP	4 ± **2**	-3.5 ± **1.5**
MVAB-0	3.1 ± **1.3**	-7 ± **3**

When optimized, MVCP and MVAB-0 both perform better than convection delay within the error bars.

Using skill scores to determine best method

Blue= overlap (one method does just as well as another within the error bars)

Green= no overlap (one method performs significantly better or worse than the other methods)

New SI list – (subset of ACE Science Center List)		
Percent Improvement on Convection Delay		
Method	**With Parameters Optimized**	**With Original Parameters**
MVCP	4 ± 2	-3.5 ± 1.5
MVAB-0	3.1 ± 1.3	-7 ± 3

…Compared to when input parameters are not optimized

Using skill scores to determine best method

Blue= overlap (one method does just as well as another within the error bars)

Green= no overlap (one method performs significantly better or worse than the other methods)

New SI list – (subset of ACE Science Center List)		
Percent Improvement on Convection Delay		
Method	**With Parameters Optimized**	**With Original Parameters**
MVCP	4 ± 2	-3.5 ± 1.5
MVAB-0	3.1 ± 1.3	-7 ± 3

When optimized, neither the MVCP nor the MVAB-0 method performs better than the other within the error bars.

What do we make from all these scores?!

After Optimization

Cross product (crossed out)	Better than CD? ✗ During optimization, never got better than CD, so we focused on the other methods Better than other tilt methods? ✗ All other methods surpass cross product
MVAB-0	Better than CD? ✓ Accounting for the error bars. Better than other tilt methods? ✗ Not better than MVCP within the error bars
MVCP	Better than CD? ✓ Accounting for the error bars Better than other tilt methods? ✗ Not better than MVAB-0 within the error bars

Research Summary and Conclusions

Geometry

- Previous research has suggested that large tilts in solar wind/discontinuity phase front planes are responsible for errors in propagation delay predictions.

Geometry

Neither non-optimized nor optimized versions of several normal-finding techniques reduce delay error for events where ACE observed a “tilted” shock far from the S-E line.

- *Conclusion*: Shock front geometry is not as clear-cut and simple as solar wind phase front geometry.

Strength

No correlations were observed between shock strength and delay error.

- Conclusion: We cannot rely on a tilted-phase-planes method simply because a shock is strong or weak.

Optimization

- 56% of MVAB-0 tilts are valid without optimization
- 25% of MVAB-0 tilts are valid with optimization

  - *Conclusion:* Optimization not only improves the accuracy of normal calculations but weeds out calculated normals that are significantly inaccurate.

Optimal methods

The optimized MVAB-0 and MVCP methods predict shock arrivals more accurately, accounting for the error bars, than convection delay and the cross product method.

- We suggest their use as shock delay time prediction methods for space weather forecasting.

Future Research

- *Knetter et al.* [2004] and *Horbury et al.* [2001] show that the cross product method does quite well as a normal-calculation technique.
    - Investigate the optimization of input parameters required for the cross product calculation with greater thoroughness than is conducted in this study

$$B\downarrow u \quad x\, B\downarrow d \qquad (6)$$

Future Research

Further investigate different parameters of shocks in an attempt to better understand which features of shocks cause inaccurate delay times.

- Our analysis suggests that shocks may have structures more complex than simply flat or simply tilted, which may be a partial factor in the calculations of invalid tilts.

Acknowledgments

The University of Colorado, Boulder – Laboratory for Atmospheric and Space Physics for organizing this research experience.

NOAA-SWPC and the NSF for encouraging and funding research at the undergraduate level.

Michele Cash for her patience, professionalism, and contagious excitement for space physics.

Questions?

Back up slides!

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Minimum Variance Analysis (MVA)

- *Sonnerup and Scheible* [1998]: Used MVA to analyze data from a satellite passing through the magnetopause boundary.
- *Ridley* [2000]: First suggested MVA as a use for Interplanetary Magnetic Field (IMF) propagation predictions.
- *Weimer et al.* [2003]: Shows that the MVA "performs reasonably well for predicting the actual time lags".

However…

Weimer et al. [2004] corrects that MVA worked only due to a "serendipitous program error, which calculated a 'modified variance Matrix'".

MVAB-0

Using skill scores to determine best method

Red = overlap (one method does just as well as another within the error bars)

Yellow = no overlap (one method performs significantly better or worse than the other methods)

Old SI list					New SI list				
	Percent Improvement on Convection Delay				Percent Improvement on Convection Delay				
Method	**With Parameters Optimized**	**Error Extremes**	**With Original Parameters**	**Error Extremes**	**Method**	**With Parameters Optimized**	**Error Extremes**	**With Original Parameters**	**Error Extremes**
MVCP	-0.4 ± 1.5	**1.1**	-5 ± 2	**-7**	MVCP	4 ± 2	**2**	-3.5 ± 1.5	**-5**
MVAB-0	0.8 ± 0.4	**0.4**	-9 ± 3	**-6**	MVAB-0	3.1 ± 1.3	**4.4**	-7 ± 3	**-4**

Strong vs. Weak shocks, optimized analysis

		FREQUENCY OF ERROR IN PREDICTED ARRIVAL TIME (%)				
Hypothesis	SHOCK PARAMETER	0-5 min error	6-11 min error	12-31 min error	Mean error (min)	Data Summary
A strong shock (Mach # used as a measure of strength) will be less susceptible to tilting if it simply blasts through the solar wind, so it will travel with a relatively flat phase front plane. Thus, a tilted-phase-planes method will better predict weaker, more tilted, shocks.	MAGNETOSONIC MACH NUMBER UPPER 50% CD UPPER 50% MVCP LOWER 50% CD LOWER 50% MVCP	77 79 75 75	13 11 21 21	8.5 11 4.2 4.2	4.3 4.1 4.3 4.1	Convection delay outperforms MVCP for both strong and weak shocks.

Highly-tilted and distantly-observed events, optimized analysis

Hypothesis	SHOCK PARAMETER	Mean error (min)	Data Summary
When ACE is far from the S-E line and observes a shock that is highly tilted away from the S-E line, a tilted-phase-planes method corrects for the error seen in convection delay.	HIGHLY-TILTED & DISTANTLY OBSERVED CD MVCP	 6 6	**No evidence that an optimized tilted-phase-planes method performs better for highly-tilted and distantly-observed events.**
	LOW TILT AND OBSERVED CLOSE TO S-E LINE CD MVCP	 2 2	